DESIGN OF AN ELECTRO - ACOUSTIC CELLO

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ABSTRACT

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By

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Factors affecting the feasibility and design of a hybrid electro-acoustic violoncello are investigated in this study. Problems of hum, noise, filter specification, and instrument configuration are discussed and solutions proposed. Circuits and techniques used in the construction of three experimental models are described, and a minimal instrument configuration is proposed for research purposes. The third of these experimental models is similar to the analog electronic violin proposed by Max Mathews of the Bell Telephone Laboratories and IRCAM.

The conclusion reached in this study is that a musically useful hybrid electro-acoustic violoncello can be built using current techniques and components, and that continuing advances in electronics should lead to rapid improvement of this type of hybrid instrument over the next decade. Possible future developments are discussed, particularly with reference to the potential of the digital filter and the use of digital techniques.

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I

HISTORICAL BACKGROUND

Musical instruments using plucked strings (such as the harp and the lyre) have been known and used since antiquity, but instruments using the bowed string appear to be of more recent origin. The earliest evidence of use of the bow comes from ninth century central Asia. By the eleventh century, the musical bow was known in Europe. It was apparently first used on instruments that had originally been built to be plucked.[1]

Before very long, new instruments were developed to exploit the musical possibilities of the bowed string. The pace of development appears to have been particularly rapid in fourteenth and fifteenth century Europe. In the century after 1450, several distinct families of bowed instruments emerged to compete with the older rebecs, vielles, and fiedels. The most prominent of these families were the viols, the lyras, and the hybrid violins, which used the playing technique of the vielles, construction similar to the lyras, and the tuning of the rebec.

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[1]Werner Bachmann, The Origins of Bowing, trans. N. Deane (Varallo Sesia, 1967), place of publication not given.

The violin family is thought to have originated in Northern Italy somewhere near the quadrangle defined by the towns of Milan, Brescia, Venice, and Genoa. Although the violin is Italian in origin, France dominated Savoy and Piedmont at the time, so that the first literary references to the instrument are in French.

In such sources these early violins are referred to as viols, vyollons, viola da braccio, lyra, lyra da braccio, geigen, fiedels, violons, or violini. Since many of these names were used for other instruments as well, the earliest references are not at all clear.[2]

The earliest definite information is found in two paintings by the Italian artist Gaudenzio Ferrari (c. 1480-1546). His "Madonna of the Orange Trees" from about 1529 or 1530 shows a small angel holding a three-stringed violin. This painting originated in the town of Vercelli in Savoy (Fr. Verceil) mentioned in the 1523 reference to money paid for the services of "trompettes et vyollons de Verceil."[3]

A later fresco by Ferrari (c. 1533) appears to show the three principal members of the violin family

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[2]David Boyden, The History of Violin Playing From Its Origins to 1761 (London: Oxford University Press, 1965); also Sheila Nelson, The Violin and Viola (London: Ernest Benn Ltd., 1972), Chap. I. The latter book is also published by Norton in the U.S.A.

[3]Boyden, op. cit., pp. 21, 22.

together. This fresco (from near Brescia) casts some doubt upon the theory that the viola preceded the violin.

Francis I of France had violinists traveling with him in 1533 and 1534; his account books for those years mention payments for such service. In the latter year, Pope Paul III brought violini Milanesi to a peace conference at Nice. In 1545, the revised version of Agricola's Musica Instrumentalis Deudsch mentions kleine Polnischer Geigen which were played without frets and with a vibrato (Zittern frey). Praetorius in 1619 also referred to the Polish Geige; Nelson suggests that the Poles imported their fiddles from Italy and that the adjective "Polish" refers to the manner of performance rather than the origin of the instruments.[4]

None of the earliest three-stringed violins survive today. Two violins attributed to Andreas Amati (dated 1542 and 1546) were supposedly converted to four strings during the nineteenth century, but no definite proof of this exists.[5] The earliest known surviving violin is currently in the Ashmolean museum at Oxford. It was built by Andreas Amati in 1564.

In 1550, the violin family was described in Philibert Jambe de Fer's Epitome Musical as an instrument for

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[4]Nelson, op. cit., p. 14.

[5]Ibid., p. 11.

professionals: ". . . added to which there are few persons who use it save those who make a living from it through their labor."[6] The violin was apparently the instrument of the professional musician and the dancing master; it had the most powerful tone of any bowed string instrument, was easily portable, and had enough carrying power to be heard in a sizable room. But because it was a professional's instrument, the violin had a low social status; musicians and dancing masters belonged to the servant class. The older gambas, perhaps the ideal amateur instruments, were easier to hold, easier to play, and well suited to the texture of equal-voiced polyphony which dominated art music. But in the seventeenth century the same qualities which had recommended the violin to the dancing master made it highly desirable for art music as well. Musical ideals changed, the growth of opera and what Caccini called "the noble voice" led to a musical texture dominated by a brilliant, florid treble and a solid bass.[7] Since the art of music was being practiced in progressively larger rooms, the violin family soon secured an important role. The viols, so satisfactory in the intimacy of a small room, could not compete in a

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[6]Philibert Jambe de Fer, quoted in Boyden, op. cit., p. 32.

[7]See Caccini's preface to Nuove Musiche, reprinted in Strunk's Source Readings in Music History (New York: W. W. Norton, 1950).

larger environment, although the bass viola da gamba managed to last beyond 1750. But by 1800 the viols were nearly forgotten.

During the sixteenth and seventeenth centuries there was a steadily increasing demand for violins. The town of Brescia was the first center for violin making, but very early in the seventeenth century Cremona assumed a dominant position. Claudio Monteverdi, a Cremonese, was one of the first composers to use the violin in art music (as opposed to dance music). The ready availability of good seasoned wood and other raw materials, a growing demand for good instruments, and a tradition of family craftsmanship led to a golden age of violin making in Italy during the late seventeenth and early eighteenth centuries. Thousands of fine instruments were built during that period; the best of these have never been surpassed in tone or beauty. The instruments of Antonio Stradivari, the Amati family, and the Guarneri family served as models for the makers of the nineteenth and twentieth centuries.

Gasparo da Salo (Gaspar Bertolotti) is often mentioned as the first violin maker, but he was not born until ten years after the earliest violin painting. Andreas Amati (now known to have been born before 1511) has a better claim, but he would have been only about eighteen at the time of Ferrari's painting. Perhaps Andreas Amati's unknown teacher made the three-stringed violins of the "Madonna of the Orange Trees," or perhaps Gaspar Bertolotti's teacher Girolamo Virchi was responsible, or Giovannia Maria dalla Corna; these men made string instruments of various kinds during the early sixteenth century. But with the scant information which has survived it seems unlikely that we can ever name the unknown inventor or inventors who developed the violin.[8]

Since the eighteenth century many attempts have been made to improve upon the violin.[9] The most important changes were made during the nineteenth century, when the neck was lengthened, its angle was changed, and the bass bar was enlarged to accommodate the needs of an expanding technique, a rising pitch, and a demand for more sound. By using heavier strings under greater tension the acoustic output was increased by increasing the energy level of the vibrating system. With this increase, the violin family managed to produce the acoustic power needed by the large concert halls of the late nineteenth and twentieth centuries.

The art of making fine violins did not die with Antonio Stradivari; excellent instruments have been made

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[8]Nelson, op. cit., p. 14.

[9]For a listing of some of the "improvements" (some patented), see Edward Herron-Allen, Violin Making As It Was and Is (London: Ward Locke and Co., 1885), pp. 104-121. This chapter makes interesting reading for any person interested in the violin.

Figure 1.--Acoustical cello: Joannes Gagliano, 1800.

since his time and are still being made today. The most valuable part of the violin, the sound box, does not wear out rapidly; some instruments over 300 years old are still in daily use. Violins actually seem to improve with playing and age, and the parts which wear (such as fingerboards, pegs, and bridges) are easily replaced. Because of this, violin makers in the nineteenth and twentieth centuries were in the position of competing with masters long dead; many found it more profitable to repair than to build. Performers generally preferred to play upon the older instruments, particularly the old Italian instruments, and many became prejudiced against playing a contemporary instrument. Makers would sometimes darken and cloud the varnish of their instruments to make them look older.

In the last few years the situation has changed. The combined effects of inflation, normal attrition, a shortage of good and properly seasoned wood, a shortage of violin makers, and a tremendous demand have all sent the prices of older instruments into a soaring spiral. Some good modern instruments are being produced, but they do not meet the demand. There is a severe shortage of competent makers and repairmen because relatively few young people are willing to serve the long apprenticeship needed to learn the craft. Many good makers are so swamped with repair work that they have little or no time to make instruments, even when it is profitable to do so again. As a result, many student (and even professional) string players are forced to perform upon instruments of unsatisfactory quality.

There exists a remarkable, in fact almost unparalleled, repertory of orchestral music, chamber music, and operatic music which depends very heavily upon the qualities of the violin family. Bartok, Schoenberg, and Stravinsky in this century have produced large quantities of good music which use these instruments, and practically every composer of note has felt compelled to write a string quartet, sonata, or symphony to demonstrate his craftsmanship. In the commercial field, violins can be heard in music ranging from Lawrence Welk to "Bluegrass" groups, and popular singers of every persuasion find violins indispensable for certain types of romantic ballads. Recent works by Lutoslawski, Xenakis, Penderecki, and Crumb suggest that the violin family has tonal possibilities which have not yet been exploited. Intonation is not limited to any particular scale; the training of the performer is the determining factor in this area. With the increase in numbers and size of civic and semi-professional orchestras and the number of string players being produced by the music schools, there are probably more violinists, cellists, etc. playing today than at any other time in history: indeed, this is one of the roots of the problem. The population increase of human performers has not been matched by a corresponding increase in the number of fine instruments.

What is it that makes the violin family useful musically? To begin with, the player is in direct contact with the vibrating medium, which offers multiple possibilities for interaction between player and instrument. In the hands of a skilled performer the violin and its relatives approach the human voice in capability for nuance and in subtlety of musical expression. The tone is relatively neutral, yet capable of wide variation in color, so that the instrument combines well with other families of instruments. Probably most important, the bowed strings can accompany almost anything. There is practically no lower limit to their dynamic range, yet in groups they can produce enough sound for most purposes.

II

THE PROBLEM

Availability of good string instruments has become a serious problem in the last few years. Inflation, limited supply, and increasing demand have combined to push the cost of the better instruments beyond what most musicians can afford. At the same time, the tendency of composers to write for smaller ensembles than the full symphony orchestra has made it desirable to increase the amount of sound produced by the bowed strings; it would be convenient for composers to have evenly matched string, wind, and percussion sound in a small instrumental group.

Why has the technology of the twentieth century been unable to improve the violin family to any extent? Probably because these instruments are compromises between conflicting requirements, some of which are not fully understood. Generations of instrument makers and acousticians have accomplished comparatively little, so the problem must be one of optimization rather than one of perfection; apparently, the makers of the early eighteenth century approached the optimal configuration very closely. Any attempt to improve the violin family should not sacrifice the instruments' useful qualities.

What are the important acoustical elements involved in an instrument of this group? To begin with, the bowed string is essential, for it produces not only the sound but also the important attack transient which is so characteristic of the sound.[10] Of the energy which is put into the string by the bow, Hutchins estimates that five to ten percent leaves the string via the bridge, and perhaps one percent is radiated as sound energy.[11] The bridge converts the sideways vibration of the string to an up-and-down motion; the treble side of the bridge is anchored by the sound post via the elasticity of part of the top, and the other side of the bridge rests over the bass bar, a long boat-shaped piece of wood which seems to couple the vibrations into the top of the sound box. The bridge acts as a transducer between the string and the wooden plates, an impedance matcher, and a tone modifier.

The sound box is the most difficult part of the instrument to control in manufacture. The top plate seems to be of particular importance; the thickest wood is immediately under the bridge, then the top decreases in thickness toward the edge of the instrument. A Stradivari violin measured by Mathews showed peaks of response at

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[10]David Wessel, "Psychoacoustics and Music: A Report from Michigan State University," Bulletin of the Computer Arts Society (1973b), p. 30.

[11]Maureen Carley Hutchins, "The Physics of the Violin," Scientific American 207 (1962, No. 5): 78-94.

some twenty different frequencies between 277 and 4500 Hz. Listening tests by Mathews and Kohut show that peak to valley ratios (in the resulting frequency response) of ten to twelve decibels seem to be near the optimum value.[12] The multiple resonances of the wooden plates (and the air resonance of the box) serve as a comb filter. The damping factor of this filter is determined by such factors as the varnish and the character of the wood. The best damping factor for a violin seems to be a compromise: too much damping of the resonances produces a harsh and unresponsive sounding instrument, too little produces a hollow quality and unevenness between notes.

Most attempts to improve the instruments of the violin family have concentrated upon increasing the amplitude of the sound. Prospects for a substantial increase in sound output from the acoustical instruments do not seem too promising at this point. Increasing one parameter beyond a certain level often seems to require a less than optimum level in another. Probably the most powerful violins extant are those of Guiseppe Guarneri, called "del Gesu" (1687-1744). Many able makers, inventors, physicists, and acousticians have tried to increase the power of the acoustical violin since that time: Their

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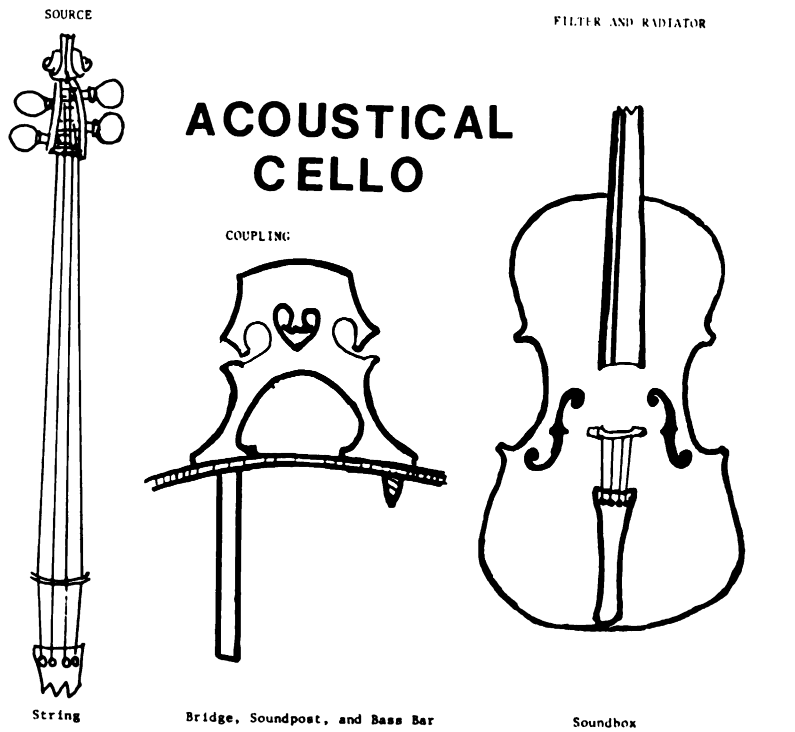
[12] M. V. Mathews and J. Kohut, "Electronic Simulation of Violin Resonances," Journal of the Acoustical Society of America 53 (1973): 1620-1626.

Figure 2.--Cello opened to show the bass bar. (Sound post in foreground).



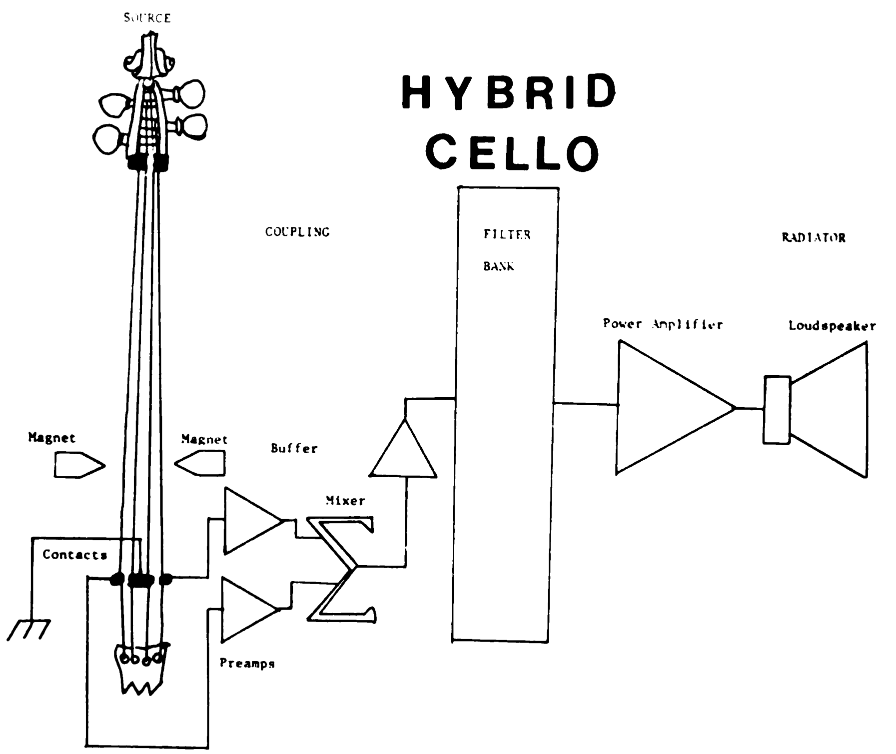


Figure 3.--Block diagrams of acoustical and electronic cellos.

limited success gives a good indication of the problem's complexity.

The electronic violin reported by Mathews and Kohut suggests an easier approach to the problems of power and instrument availability.[13] The string is conventional in Mathews' violin, but the bridge is thick and transmits a negligible amount of sound energy to the body. The string is made to vibrate in a strong magnetic field. The current produced as the string cuts the magnetic lines of force is run through a bank of electrical filters which simulates the wood and air resonances of the acoustical instrument. The resultant signals are combined, amplified, and used to drive a loudspeaker.

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[13]Ibid.

III

RESEARCH, 1974-1976

It was suggested by Dr. David Wessel of the Michigan State University faculty that Mathew's electronic instrument approach could be extended to the violoncello or bass. It was further suggested by Dr. Russell Friedewald that such an instrument would be more acceptable to conventionally trained musicians if it were self-contained, not requiring an auxiliary sound system. So with encouragement from several faculty, and particularly from Dr. Wessel, preliminary work was begun during the first months of 1974.

A musical instrument is a highly sophisticated device; most instruments have evolved over a period of many years, with contributions from many makers. For this reason, the research was not begun with the idea that a finished instrument would result; the purpose of the research was (and still is) to determine how close we can get to a satisfactory instrument at the current level of technology.

Several questions could be raised about the electronic approach. The most important are:

1. Why not just use a microphone and amplifying system, if the acoustical instrument is so satisfactory? This approach has been used in the commercial field, but in live performance there are severe problems of feedback and microphone positioning (close enough to allow a reasonable level of amplification, yet far enough away to avoid string noise pickup and difficulties with the radiation pattern of the violin); the best microphones and speakers are barely good enough for the job. Contact microphones solve some of the feedback problems, but they have not been noted for their fidelity and they reproduce the instrument vibration only at the point of contact. Instrument noise is also a problem. Most important, this approach does nothing to help the problem of the instrument shortage.

2. Why not go further and substitute an electronic device for the string? There are several reasons for preferring the bowed string at this time, including the characteristic sound of the bowed string (the attack, pitch jitter, and inharmonicity), multiple opportunities for the performer to interact with the instrument, and the existence of a large, varied, and high quality literature which could be performed on a hybrid instrument that combined the conventional bowed string with a set of electronic resonances.

It seemed highly likely that such a hybrid cello might be both possible and musically useful. One problem which did not concern the Mathews violin seemed likely to cause difficulty. The commercial power frequency in this country is 60 Hz, about half way between the b-flat and b-natural two octaves and a second below middle c. This is adjacent to the cello's lowest tone at about 65 Hz. Appreciable electrostatic and electromagnetic fields exist wherever there is a power line, and a length of wire which is not shielded will have a 60 Hz voltage induced in it. An electronic violin's response can be reduced below 190 Hz, but this is not possible with an electronic cello. Preliminary studies with magnets and a conventional instrument indicated that the desired signal would be only a few millivolts and the hum at 60 Hz nearly equal to that, or in a worst-case situation possibly several times the signal. It seemed likely that some special techniques would be necessary. The type of magnetic pickup used by Mathews seemed the simplest, but it was inherently susceptible to both electromagnetic and electrostatic fields.

A similar hum pickup problem occurs when very long cables are used with microphones. In order to avoid the loss of high frequencies in long microphone cables, it is necessary to use a low impedance microphone. The output of these microphones is only a few thousandths of a volt, however, whereas the hum voltage produced on a cable several hundred feet long may be many times that. The problem is solved by using two shielded lines which are balanced with respect to ground (the shield). A transformer is connected at the end of the cable in such a way that the amplifier amplifies the difference between the signals; the induced hum is common to both lines, and consequently cancels. Some electric bass guitars use a "hum-bucking coil" to produce a similar cancellation. This is a coil of many turns of fine wire which is oriented to cancel the voltage induced by the power lines in the regular pickup coil. (It should be noted that electric guitars use a variable reluctance type of pickup, unlike the Mathews instrument in which the string itself generates the current.)

Since it seemed impractical to enclose player and instrument in a grounded metal shield, a hum-bucking coil was considered. However, the reactance of this coil would tend to delay the rise time of the higher frequency components, an undesirable situation. The idea occurred that the strings themselves might be arranged to cancel the undesired hum.

To try this idea, a test-bed instrument was constructed in the early spring of 1974. This first prototype was designed to test possible pickup configurations and investigate the hum problem. It consisted of a board about 79 cm long, 25 cm wide, and 2 cm thick. At the top of this board were a fingerboard, neck, pegbox, and scroll taken from a defunct plywood cello. At the bottom was a tailpiece taken from the same instrument. Four cello strings were stretched between the pegbox and the tailpiece, and a cello bridge placed about 168 cm from the nut at the end of the pegbox. Two pieces of tinned copper braid connected the strings together in pairs at the nut so that alternate strings were connected in opposite directions. A series of alligator clips connected the strings (on the lower side of the bridge) to a Cannon connector. The two middle strings were connected to pin one on the connector (ground) and the outer strings were connected to pins two and three. This connection allowed the use of balanced microphone cables and an in-line microphone transformer for hum cancellation. It was found possible to use a moderately long cable (up to 30 feet) before the hum level became objectionable. An audio amplifier with a microphone input served to amplify the signal.

This first prototype sounded somewhat like an acoustical instrument on the lower strings, but had a harsh and rough sound on the A string. Vibrato seemed to produce little or no effect upon the sound. The results in hum reduction were encouraging enough that a second prototype was planned to test the feasibility of an instrument with a self-contained speaker.

The second prototype used the first prototype as a component. Plywood sides, back, top, and bottom were added to the first model to form a kind of loudspeaker cabinet, and an inexpensive co-axial speaker mounted in the back. The problem to be investigated was that of acoustical feedback: Would it be possible to run a reasonable amount of power into the speaker without having feedback from speaker to string set up a continuous oscillation? The sides of the enclosure were sloped outwards and the back made wider than the front so that the speaker could be mounted without interfering with the bow arc. The axis of the speaker approximated a right angle to the plane of vibration of the strings; this mounting was planned to minimize acoustical coupling between speaker and string. No attempt was made to optimize the musical qualities of the instrument because this model was intended primarily for research on the feedback problem.

This second prototype proved that the feedback problem was less severe than had been anticipated. Furthermore (and most unexpectedly), it sounded astonishingly like an acoustical instrument. In fact, the second prototype sounded more like a cello than many plywood student cellos do. Apparently there were enough stray resonances in the inexpensive speaker and cabinet to simulate many of the resonances which give the acoustical instrument

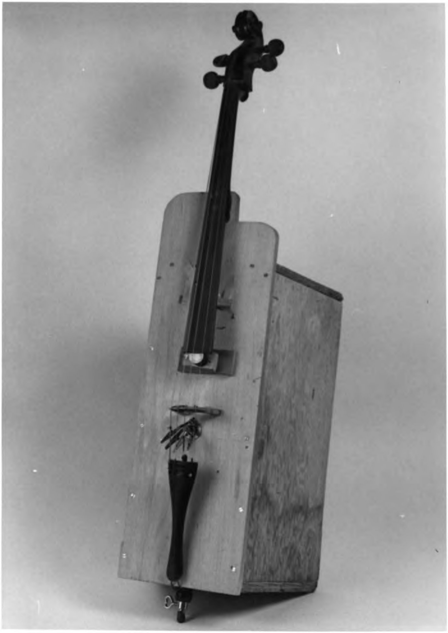

Figure 4.--Hybrid cello: second prototype.

its quality. However, this model did not approach the quality of a good acoustical cello.

The second prototype also established that the alligator clip was not a desirable means for making electrical contact with the string. The formation of oxides on clip and string winding created intermittent contact problems. The tinned braid contacts used at the nut worked well, however, probably because the tension and sliding motion of the string caused by tuning served to polish the contacting surfaces. Consequently, the clips were replaced by silver-plated braid contacts mounted directly on the bridge. The braid was of the type used to pick up excess solder from high density circuit boards. A better solution to the contact problem would be to use gold inserts set into the bridge and nut, but the braid contacts worked well enough that the extra expense of these inserts was not felt to be necessary at this point.

The second prototype, like the first, used whatever amplifier was convenient. When the filter system was added it was found that many of the preamplifiers found in high fidelity systems had either too high an output impedance or tended to overload (clip) before the desired dynamic level was reached. The long lines from string to preamplifier also added a noticeable amount of hum to the signal. It seemed evident that a good low-noise preamplifier mounted close to the string would improve system performance. For reasons of compactness and economy, an integrated circuit appeared the best choice.

An article by Jung on the problems encountered with operational amplifiers in audio circuits indicated that the 739 dual stereo preamplifier should be a good choice for this application because of its low noise, wide bandwidth, and high gain.[14] The first attempt to build the preamplifier (using a circuit from the application notes which accompanied the device) established that the 739 was an even better oscillator (at about 4×10^5 Hz) than it was an amplifier. Some experimentation was necessary to tame the 739, but once domesticated it proved to be an excellent performer. It was necessary to use a two-sided circuit board, with the foil on the component side acting as a ground plane. All ground connections were made to this foil with the shortest connections possible. Even with these precautions, it was found necessary to bypass the summing junction of the amplifier directly to ground with a disc-ceramic .003 microfarad capacitor to prevent instability. The half-power points on the response curve of this preamplifier were below 10 Hz and above 60,000 Hz. Following the 739, a 741 was used as a

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[14]Walter Jung, "The Pitfalls of the General-Purpose IC Operational Amplifier as Applied to Audio Signal Processing," Journal of the Audio Engineering Society 21 (1973, No. 9): 706-714.

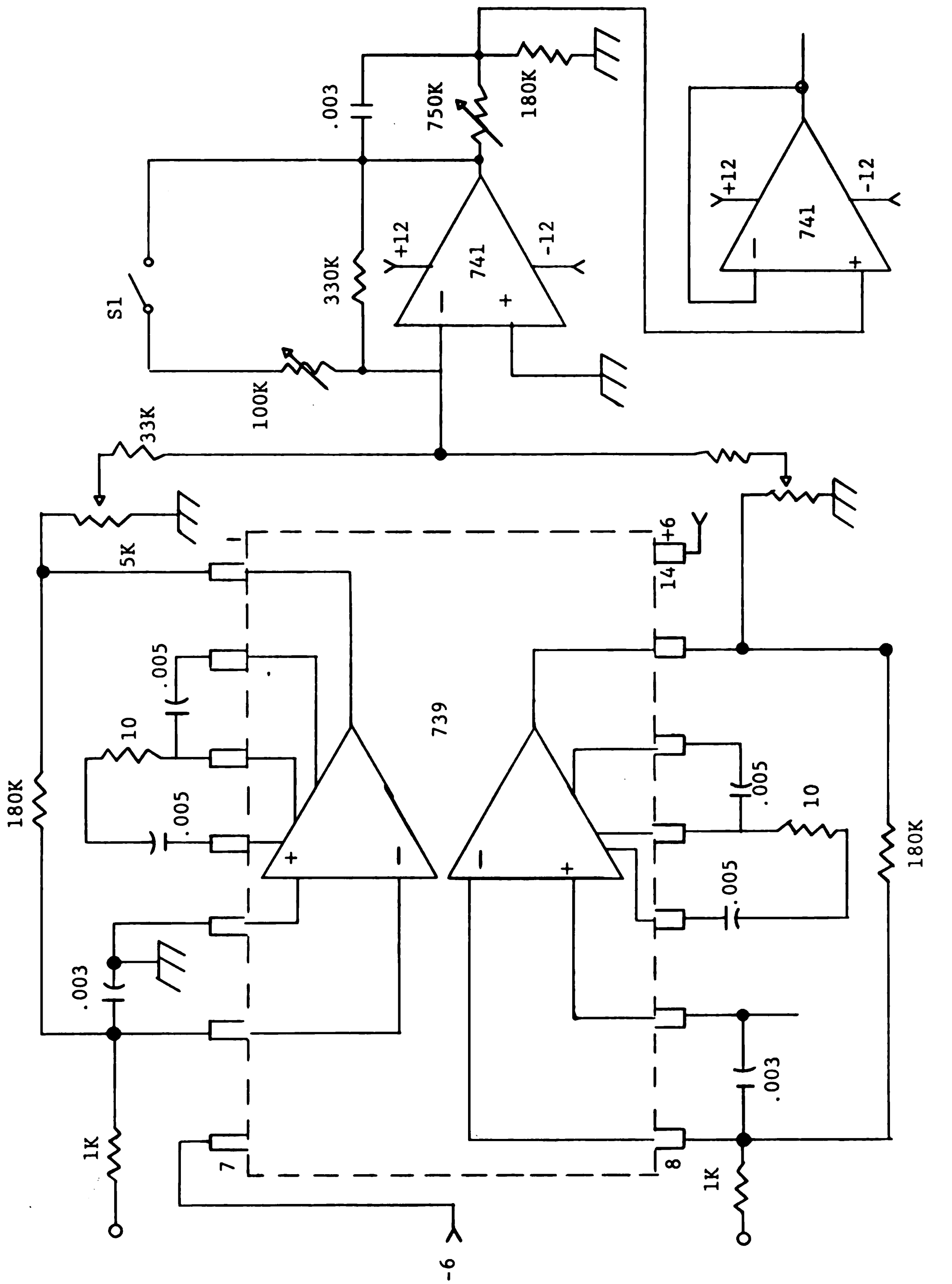

Figure 5.--Schematic Diagram of Preamplifier.

low-gain virtual ground mixer to combine the output of the two preamplifiers contained in the 739 chip. The gain of the 741 was adjustable; the entire system had a gain of 47 decibels in the lower gain setting; in the higher gain setting, 57 decibels were available. Each channel of the preamplifier also had its own potentiometer for individual adjustment.

The noise output of the preamplifier measured just under four millivolts peak-to-peak on a sensitive oscilloscope. Since the preamplifier was in its high-gain configuration (gain of 750) this would indicate that the equivalent noise voltage at the input was on the order of 5 microvolts (.000005 volts). The noise level increased to about 5 millivolts peak-to-peak at the output when the string was connected. This was probably due to excitation of the string by room noise or vibrations, for no 60 Hz component was detected on the oscilloscope. The preamplifier clipped at 8 millivolts peak-to-peak input; the clipping was observed in the 739, not in the following stages. This low overload point could be reduced if necessary by using a lower gain in the 739, then adding more stages after it.

In the second prototype some difficulty occurred with radio-frequency interference, or RFI. The local broadcast station could be heard distantly but distinctly. The condition manifested itself particularly when the clip contacts in the early model developed an oxide layer. The RFI problem was solved by shielding all leads near the pick-off point, bypassing the leads to the shield with .001 microfarad disc-ceramic capacitors, and by changing to braid contacts rather than clip contacts. When the 739 preamplifier was finished, it was mounted in a grounded metal box and the input leads bypassed with disc-ceramic capacitors also. There was no further difficulty with RFI.

Instruments of the violin family have multiple resonances. The theory of timbre modulation which Mathews advanced to explain the effect of the violin vibrato depends on these multiple resonances, which are produced by the body and air resonance of the instrument. In a series of listening tests Mathews and Kohut established some criteria for the resonances necessary to produce a rich violin tone. Their conclusions were:

A. Peak frequencies need to be spaced so that the harmonics of the tone do not fall on either all positive or all negative slopes of the filter characteristic. A random distribution is satisfactory, but an exponential distribution gives a more uniform response (an exponential distribution has a constant musical interval spacing on the average).

B. The damping of the resonances must be such that the "Q" or quality factor (inversely related to the damping) of the resonators makes the response curve steep throughout the filter characteristic. (That is, the derivative or rate of change of the filter amplitude with respect to frequency must be large

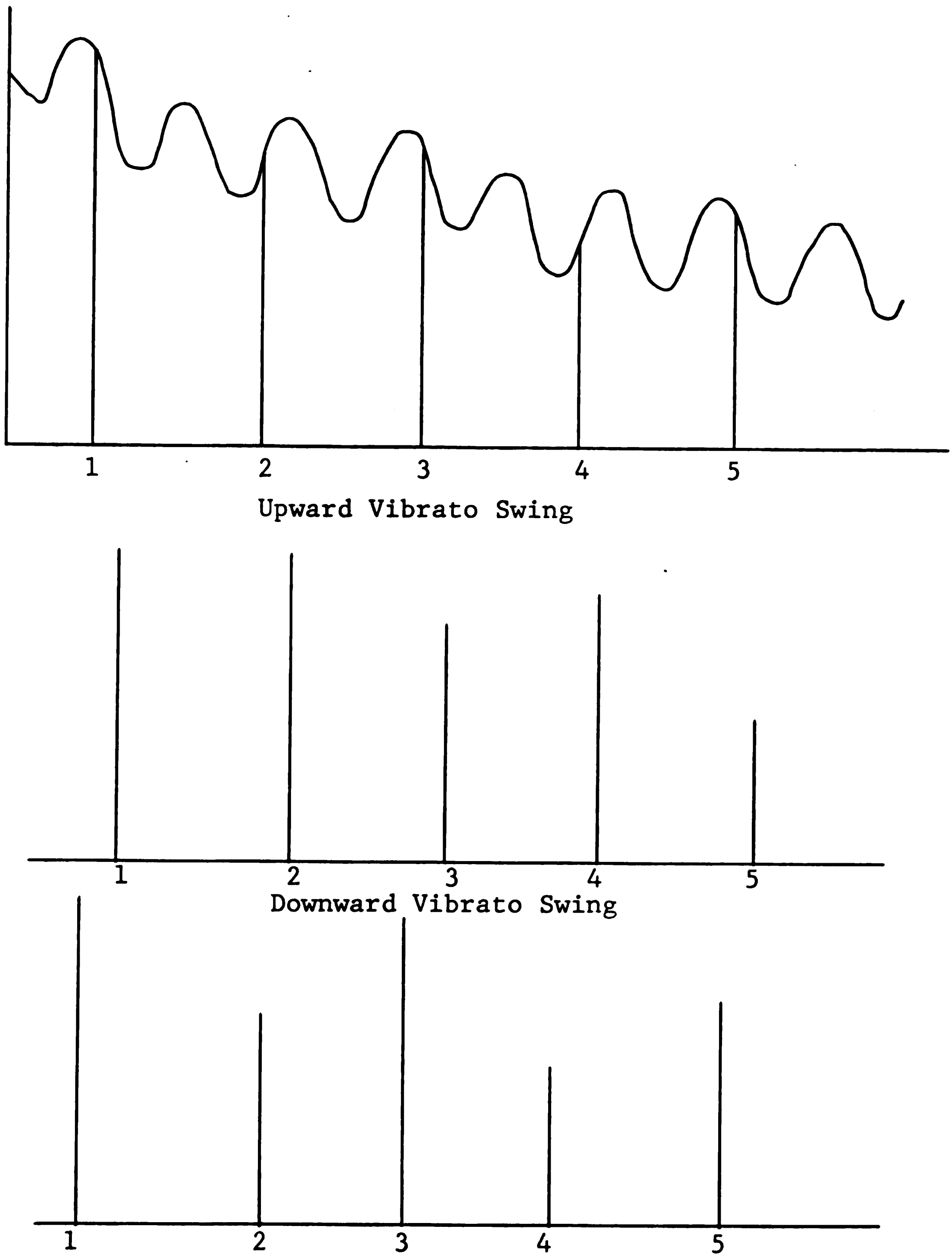

Figure 6.--Relation of string overtone to Mathews' filter.

throughout the range of the filter; if the derivative is too small, the timbre modulation effect is lost).

C. The peak frequencies of the resonances need to be spaced closely enough that the depth of the intervening valleys does not exceed fifteen decibels. If there are large spectral gaps in the tone, it sounds hollow to the listener.[15]

These criteria suggest that a violin needs 20 to 30 resonances spaced quasi-randomly (or exponentially) in the range between 200 to 5000 Hz. Mathews estimates that the figure of 24 resonances is about optimum for a violin. Since a cello may play nearly as high as a violin, its filter response should probably extend to at least 4000 Hz. More resonances are necessary as well for the musical twelfth of range that the cello has below the violin's lowest string. Assuming an exponential spacing of about 6 resonances to the octave, it seemed that 30 to 36 resonances should be adequate for an electronic cello simulation.

A filter of any sort is characterized by its ability to pass certain components of a mixture while rejecting others. Electrical wave filters work similarly, but instead of straining out physical particles they dissipate the undesired component as heat. Mechanical filters will give better results in some applications than a realizable electrical filter; in other applications they

[15]Mathews and Kohut, op. cit., p. 1624.

are less satisfactory.[16] The advantage of the electrical wave filter is that it is easier to build. Mechanical filters inevitably exhibit some loss. Electrical filters made up of passive components also have losses, but the availability of electronic amplifiers makes it relatively simple to bring the desired components back up to the original level, or to a higher one. A filter which uses an amplifier as an integral part is an active filter, which has no loss.

Electrical wave filters are generally classified as low pass, high pass, and band pass. The filter characteristic exhibited by the violin family is a variety of band pass filter known as a comb filter because of the resemblance of its response chart to the teeth of a comb. The mechanical filter which produces this response is made up of the wood and air resonances of the instrument. This filter has very good signal-to-noise ratio, but shows a high loss, is difficult to tune, and nearly impossible to reproduce exactly, since no two pieces of wood are identical. Even a master luthier cannot be certain that all of his instruments will be uniformly good.

Filters can be implemented in many ways. The most common form in the range from 1000 to 100,000,000 Hz is

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[16] Anatol Zverev, Handbook of Filter Synthesis (New York: John Wiley and Sons, 1967).

still the inductance-capacitance filter, although in recent years other types have been displacing it in many applications. This type of filter is generally called an LC filter from the electrical symbols for inductance (L) and capacitance (C). At the lower end of this range, resistance-capacitance (RC) filters can also be used, but these do not match the LC filter in performance unless active devices (such as integrated circuits or transistors) are used to provide gain or impedance transformation. When this is done, they become active filters. LC filters leave something to be desired at low frequencies.[17] The low Q (quality factor), large size, and high price of the inductances needed in the range below 1000 Hz make the LC filter undesirable for the application under consideration.

An integrated circuit called the operational amplifier serves as the gain element in most active filters. Ideally, the operational amplifier has infinite gain, infinite bandwidth, infinite input impedance, zero output impedance, and generates no noise of its own. In the real world, of course, there is no such amplifier, but a good operational amplifier may have a gain of over 100,000, an input impedance of 250,000 to 1,000,000,000 ohms, unity gain crossover in the Megahertz range, an

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[17] Zverev, op. cit., p. 22.

output impedance under 100 ohms, and some also have low noise. This performance approximates an ideal amplifier closely enough that it is possible to proceed as if it were in fact an ideal amplifier. The error introduced by this assumption is usually small, for operational amplifiers are generally operated with large amounts of negative feedback, which improves most other parameters at the expense of reduced gain.[18]

Operational amplifiers have two inputs: one, the non-inverting or + input, produces an output of the same polarity as the input (in phase with the input). The other, the inverting or - input, produces an output opposite in polarity to the input (out of phase). The gain of the amplifier is set by connecting the output to the inverting input through a voltage divider. The resulting negative feedback stabilizes the gain over a wide frequency range, raises the input impedance (which reduces the loading effect of the amplifier upon the signal source), reduces the output impedance (this reduces the effect of the coupling circuits between the amplifier and the following stages upon the frequency response and power bandwidth), tends to suppress noise and distortion, and makes the performance of the amplifier less sensitive to

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[18] H. Ahmed and P. J. Spreadbury, Electronics for Engineers (Cambridge: Cambridge University Press, 1973). Chapters 4 and 5 contain a good discussion of negative feedback and the operational amplifier.

such parameters as supply voltage, temperature, noise and ripple from the power supply, and so forth.

In theory an operational amplifier can be used in building-block fashion to produce gain in a circuit with no need to know more about the device. In practice things are not quite that simple: there are certain very definite limits and precautions which must be observed to prevent the sudden demise of the device. Furthermore, the practical amplifier does not have infinite frequency response. Because of the time it takes to charge capacitances within the device there is a progressive phase delay and decrease of output with an increase in frequency. If the gain of the amplifier drops below unity before the phase delay at the output reaches 180 degrees, the amplifier remains stable. But if there is still appreciable gain at this frequency the amplifier may become an oscillator. This can be prevented by limiting the gain at higher frequencies through a process called compensation. Some integrated circuit operational amplifiers, such as the 709 and 739, need external components for compensation; others, such as the 740 and 741, have it already built in. The internally compensated amplifiers are easier to use but less satisfactory for wide bandwidths and high frequency use.

The 741 operational amplifier is inexpensive, compact, tolerant of abuse, and the most foolproof of the integrated operational amplifiers. Since the original Mathews filter used the 741, forty of these devices were ordered in the summer of 1974. Six months and two back-orders later, the amplifiers arrived. In the meantime, a letter from Herbert R. Willke, Jr., of the Bell Telephone Laboratories to Dr. William Hartmann of the MSU Physics Department described a new filter circuit and a procedure for tuning the individual resonators. The new filters used 5558 operational amplifiers and claimed a 70 decibel signal-to-noise ratio. Since the 5558 is essentially two 741s in one package and a substantial investment had already been made in that device, the latter were substituted for the 5558s (see Figure 7). The input capacitor (C 1 in Figure 7) was ceramic, as in Mathews' filter, but the larger capacitor, C 2, was changed to a Mylar dielectric in order to get better capacitance stability under the thermal cycling caused by soldering. These were ordered in October of 1974, but the distributor lost the first order and back-ordered the second. Actual delivery did not occur until January of 1975.

From January through late April of 1975, the filter was built and tuned. The resonator circuit boards were drawn, etched, drilled, and plated, and an aluminum chassis was modified to become a card cage for the boards. Contact fingers on the board were spaced to fit some surplus edge connectors already on hand, and these sockets

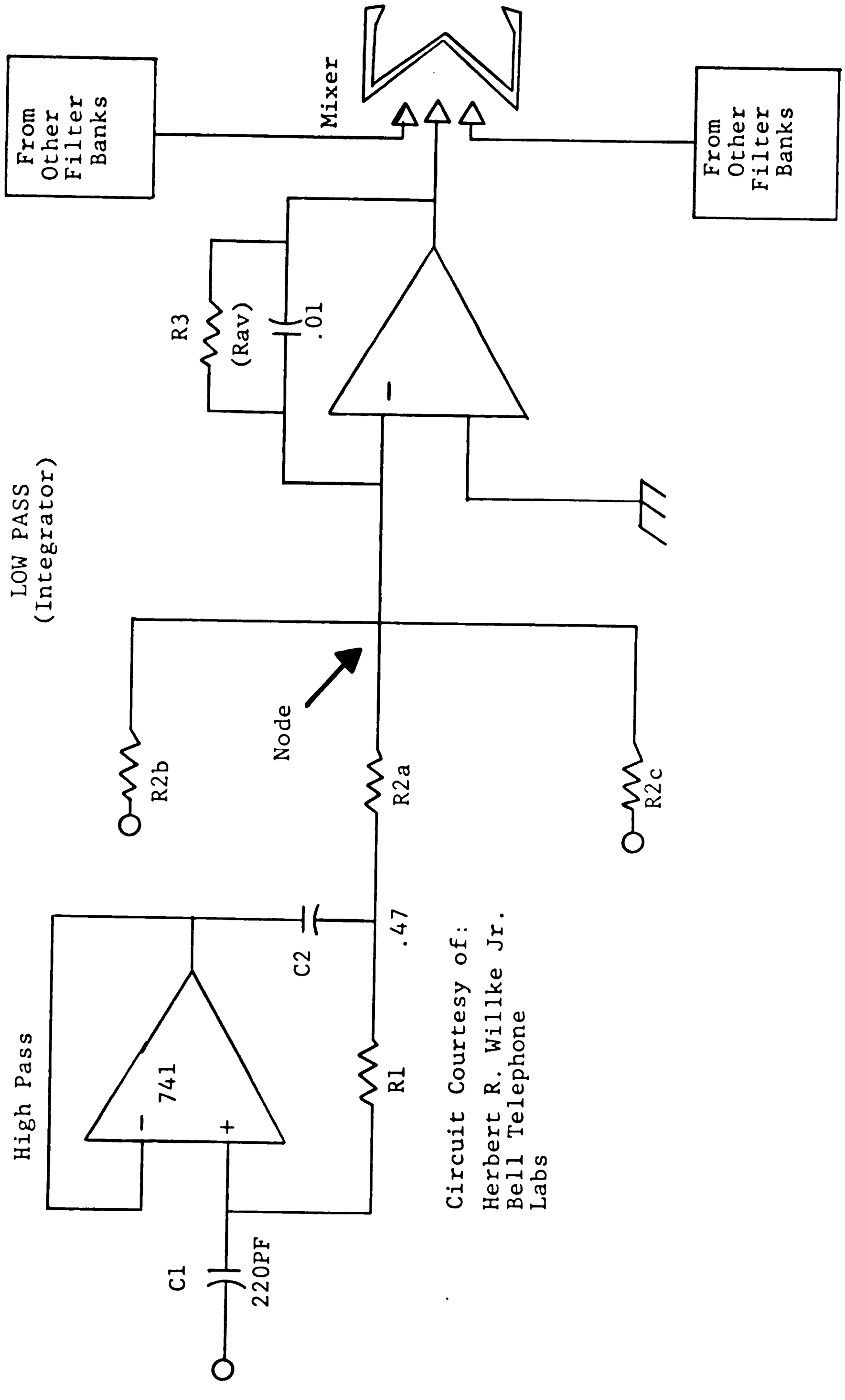

Figure 7.--The filter: schematic diagram.

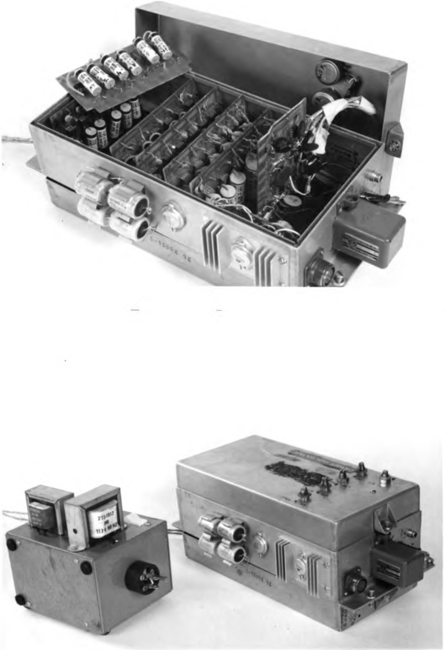

Figure 8.--The filter and power supply.

were mounted in the cage. A small hand wire wrapping tool was used to interconnect the sockets; this allowed the connections to be changed easily if the need should arise. Socket pin strips (called Molex® pins) soldered into the board allowed easy interchange of operational amplifiers, and terminals let into the board served to mount the resistors and capacitors. During the developmental period the filter drew its power from a home-made tracking bench supply.

About fifty .47 microfarad capacitors were compared on an improvised bridge circuit to get a group of 24 which varied from about .42 to .5 microfarads. These served as C 2 for the upper four octaves of the filter bank. For the lower octaves, values of .68, .82, 1.0, 1.25, and 1.5 were used. To avoid inaccuracies in tuning caused by heat cycling these were soldered in, one lead at a time, with an overnight cooling period between. The 220 picofarad capacitors (C 1) were bridged and soldered in a similar fashion, but the largest values of C 2 were paired with the smallest values of C 1, as Willke suggested. Two of the 220 picofarad ceramic capacitors were paralleled for C 1 in the lowest octaves.[19]

The tuning of the resonators was accomplished by substituting different 5 percent tolerance values for R1

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[19]The procedure for tuning the resonators follows closely that suggested by Willke in his letter to Hartmann.

and R2 in Figure 7. The center frequency was established by interpolation between the half-power points as measured by a calibrated audio oscillator, a frequency counter, and an oscilloscope. With some practice it was possible to tune each resonator in increments of less than one semitone. To avoid confusion between resonances while tuning, only one resonance was enabled at a time until the entire card was tuned. Home-made clips held the resistors in place during the tuning process and facilitated substitution. The resistors on each board were soldered in place permanently after all six had been tuned. Care was necessary during the soldering, for the resistors would change value permanently if allowed to become too hot. The use of heat sinks and cooling periods (between each joint) helped, but in spite of these precautions some resistors shifted far enough that re-tuning became necessary.

Target frequencies for the filter were chosen to approximate Mathews' choices in the upper four octaves, and to approximate one-sixth octave spacing in the lowest two octaves. Octave or multiple octave duplications were avoided and peak frequencies chosen so that 60 and 120 Hz were near response minima. The frequencies of this filter and Mathews' original filter are compared in Table 1.

Initial results with these filter boards were both encouraging and discouraging: the former because the tone quality was good, the latter because a severe

TABLE 1.--Filter frequencies (in Hertz).

Mathews' Violin Filter	Cello Filter
4500	4600
4186	4300
3600	3600
3050	3000
2800	2800
2489	2400
2290	2100
1976	1900
1760	1700
1480	1400
1360	1200
1245	1100
1109	970
988	920
905	730
720	520
565	430
466	370
392	330
277	300
	270
	240
	220
	190
	170
	160
	130
	117
	104
	86
	78
	67

noise problem appeared. Although individual resonators approached the 70 decibel signal-to-noise ratio claimed for the circuit, the filter as a whole did not, particularly at the upper end of the passband. Not only did the average noise level increase as resonators were added, but also bursts of noise were noted that peaked at three to ten times the average noise level.[20] Besides these, a burst of noise seemed to recur regularly at about 120 Hz; when this was compared with the residual ripple voltage on the power supply line (using a dual-trace oscilloscope) the two were found to be nearly synchronous. It seemed that some of the 741s had poor common mode rejection, particularly at the higher frequencies. The wide variation in noise level suggested that some devices were very much better than others as far as noise performance was concerned. On the advice of Dr. William Hartmann the noisier units had different devices substituted for them. This improved the average noise level only a little, but the burst noise was improved dramatically.

The measured electrical signal-to-noise ratio of this filter was only 46 decibels. Unfortunately, the perceived ratio was worse than this because of the low signal energy at the frequencies where the human ear is most

[20]This may be the "popcorn noise" mentioned by Walter Jung, op. cit., p. 712.

sensitive; measurements taken in the MSU audiology laboatory (using a sound level meter weighted to approximate the response of human hearing) gave a perceived ratio of only 30 decibels. By using a DBX(r) expander after the filter it was possible to shut down the noise when the instrument was not playing so that the cello was usable, but without this volume expansion the instrument put out a steady and very noticeable "whoosh" when it was not being played. The signal-to-noise ratio of the filter was simply not adequate for the application. High frequency pre-emphasis before the filter combined with deemphasis after the filter helped somewhat, but not enough.

Several discouraging months followed, in which it seemed that the whole project was probably futile. Fortunately, Dr. James Beauchamp of the University of Illinois visited the MSU campus in the early spring of 1976. While here, he did an analysis of the filter circuit and made several useful suggestions. Particularly, he suggested that one filter section should be "breadboarded" to see what, if any, effect changes in component values might have upon the noise performance of the filter. The suggestion was followed immediately.

The filter circuit is not the usual type of active band-pass filter; it consists of a high-pass section followed by an integrator which serves as a low-pass filter. The combination of the two gives a band-pass characteristic.

While experimenting with different values of resistance and capacitance it was noted that the integrator began clipping long before the high-pass section. The obvious step was to reduce the gain of the integrator, which was done by changing the original high value of feedback resistor (R3) to a value which was the average of the R2s from the high-pass sections.[21] This gave the integrator approximately unity gain, and improved the overload characteristic by a factor of 15. The mixer circuit which follows the integrator also was reduced to unity gain. The modified filter overloaded very gradually at an input level of five volts and had a residual noise level of about .0002 volts, which indicated a signal-to-noise ratio of about 87 decibels.

When the integrators in the filter bank were modified it was discovered that by inadvertence some of the capacitors had been put in originally with a wrong value; these were changed to the recommended value during the modification process. The result of these changes was a filter that was adequate for its job. The overall signal-to-noise ratio of the filter measured in excess of 70

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[21]Because of the node or virtual ground which exists at the inverting input to the integrator, it is possible to use several high-pass filters for each integrator. If too many are used, however, there will be an increase in gain from the lower frequencies to the higher because the tuning resistors of the high-pass sections act as the input resistors to the integrator, which changes the effective feedback.

decibels (approximately the same as that of a full symphony orchestra). By careful pre-equalization and trimming of the filter response that figure could possibly be improved a little more. Tests in the audiology laboratory at MSU suggest that the perceived value is fairly close to this figure also, although a malfunctioning sound level meter prevented a definitive measurement. Most of the remaining filter noise appears to be at the power supply ripple frequency and its harmonics. It is planned to bring this ripple down as far as possible in the next model of the filter.

The distribution of gain in the system is crucial; the best strategy for a low noise level is to put as much gain as possible before the filter. Since the noise also depends upon the source impedance seen by the filter, the preamplifier should have as low an output impedance as possible. A circuit called a voltage follower was used between the output of the preamplifier and the line to the filter in order to get the lowest possible output impedance. A voltage gain of about 1000 between the string and the filter input seems to be about optimum in this system; any less and noise becomes a problem, any more and clipping is likely.

The power supply is also critical. The ripple frequency and its principal harmonics necessarily fall within the passband of the filter and the response of the speaker in an electronic cello. Very good filtering of the D.C. power is vital. Most operational amplifiers call for a split supply, that is, one in which the common ground point is approximately half way between the positive and negative voltages. Reduction of residual A.C. ripple is best accomplished by an active filter circuit which also serves to regulate the voltage output. In the last few years completely integrated regulators and filters which are conveniently packaged have become available at a reasonable price. The filter of Figure 9A appeared to be simple, economical, and capable of the desired ripple reduction. Unfortunately, this proved to be true for the positive side of the supply only. Since the positive side of the supply was satisfactory, it was used as the reference for a 741 inverting amplifier. The current output of this 741 was increased to the needed level by two Darlington-connected power transistors. The output voltage of the resulting composite operational amplifier was sensed by a resistive divider between the positive and negative output terminals, and fed to the inverting input of the 741. Since the non-inverting input of the 741 was connected to ground, the output of the negative supply acts to force the inverting input to ground also. By trimming the voltage divider it was possible to make the negative supply track the positive supply with the same low ripple content. Several thousand microfarads of

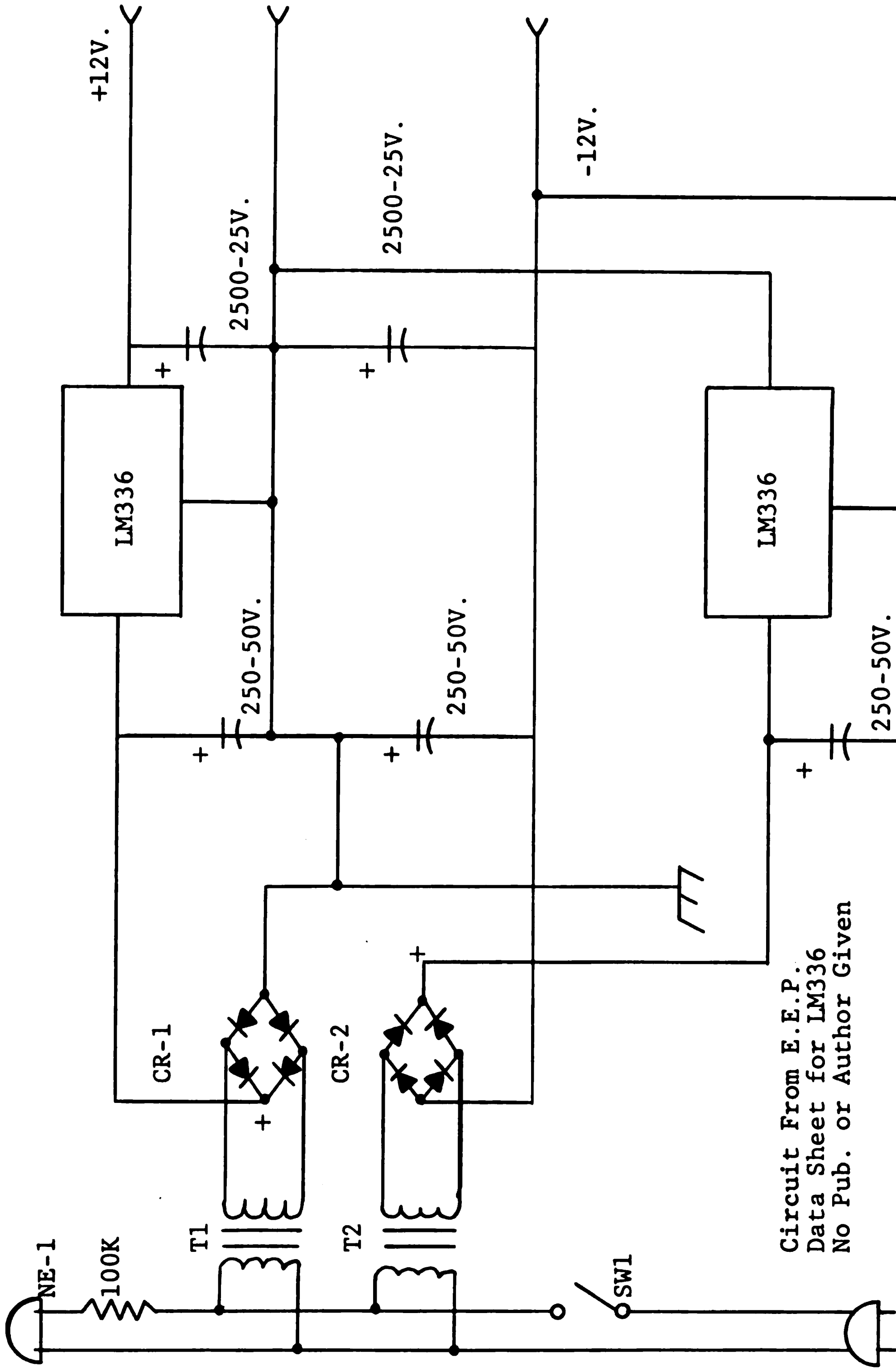

Figure 9a.--First power supply circuit diagram.

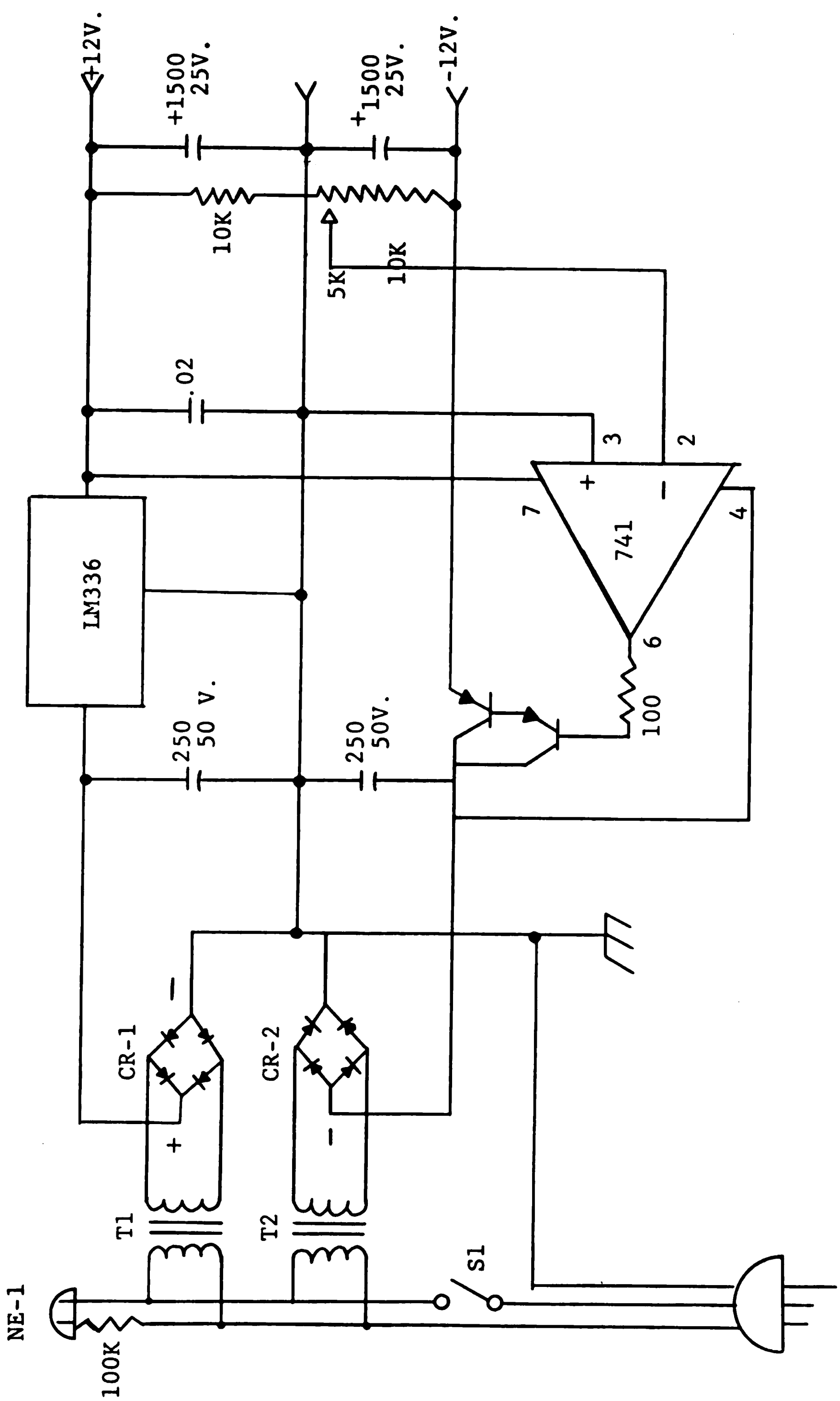

Figure 9b.--Second power supply circuit diagram.

filter capacitance were mounted near the sockets of the filter boards to decouple the filter banks; it was observed that this reduced the noise of the highest filter bank by several decibels. The power leads were long, of narrow gauge wire, and unshielded, so this additional capacitance at the board is probably a good idea. To prevent capacitive or inductive pickup from the power line the transformers, rectifiers, and initial filter capacitance were mounted in a separate chassis at the end of a 20-foot run of shielded wire. This was probably not strictly necessary, but seemed a good idea at the time. The improved power supply (Figures 8 and 9B) had a measured ripple voltage of .0007 volt.

The power amplifier for an electronic cello poses no particular design problem. Nearly any good quality audio amplifier will do the job as long as it is capable of producing the desired output power with low distortion. During the development period a 10-watt amplifier from the RCA Transistor Manual powered the instruments described here.[22] The choice of an amplifier depends largely upon the power requirements of the speaker system. The Signetics SE540/NE540 power driver integrated circuit seems promising for this application; with the addition

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[22]RCA Transistor Manual, Technical Series SC13 (Somerville, N.J.: RCA Corporation, 1967), pp. 484-487.

of appropriate output transistors and a few components this device can produce output powers in excess of 35 watts with low noise, low distortion, low cost, and compact packaging. It also contains an effective protection circuit. Some of the new hybrid amplifier modules may also be suitable.

The power needed from the amplifier depends largely upon the speaker system and the maximum sound pressure level (SPL) desired. Speaker systems vary widely in efficiency and accuracy. In general, there are compromises involved between these two factors and the size of the enclosure, particularly at the lower end of the audio range. At present the manufacture and design of speaker systems seems nearly as much an art as a science. The field is highly competitive and new designs appear from time to time, but most speaker systems are some sort of variation upon a few basic designs, such as the infinite baffle ("acoustic suspension"), the bass reflex, the loaded horn, the electrostatic panel, or some similar design. In the last several years more exotic designs such as the Ohm F and the Magnepan have come upon the scene, but most of these require large driving power and would be a poor choice for this particular application. One new design which may prove useful for electronic instruments is the motional feedback speaker, such as the Phillips system, in which the motion of the speaker cone is compared with the exciting voltage and corrected if necessary by electronic means. This system has a high sound output in a relatively small package; this would seem to be advantageous in an instrument speaker.

The accuracy requirements for a student-level-instrument speaker are not as stringent as for a speaker designed for high-fidelity reproduction of music. Substantial acoustical energy is not needed below 60 Hz or above 5000 Hz, and uneven reponse can be at least partially compensated by trimming the output of the speaker bank. Any remaining speaker coloration becomes a part of the instrument's characteristic sound. Sound pressure levels of 85 decibels or more are needed (down to 60 Hz) in order to compare with the output of a good acoustical instrument. But for an instrument of concert quality, particularly one which used a programmable digital filter, a speaker would be needed which combines high accuracy, wide frequency range, and a high sound-power output capability. This is a severe requirement.

The choice of speaker depends upon the sound pressure level which must be produced. If a very high SPL is desired, then a separate speaker system is a necessity to avoid acoustical feedback. For more normal levels a built-in system is more convenient. A good compromise might involve a small amplifier with an efficient speaker which could be run at moderate (i.e., normal) levels for several hours from a rechargeable battery pack. This amplifier could also drive a set of stereo headphones for many hours of practicing. If more power should be needed, an external high-powered amplifier and speaker could be connected via a line output jack.

An interesting possibility for an inexpensive student instrument would be to take advantage of the fact that most speaker systems have peaks and dips of 5 to 15 decibels in their response characteristic. These speaker resonances could substitute for instrument resonances (as in the second prototype) with additional resonances added as necessary by a filter bank to get the desired tone quality. Some economies could be realized by this configuration, but an equalizer would be required if the output of such a filter should be fed to an external speaker system.

IV

INSTRUMENT CONFIGURATION

There are a number of ways in which a hybrid instrument of the Mathews type could be constructed; for example, the strings could be placed on a kind of a table, zither fashion, and played with a rotary motor-driven bow. There is no reason a hybrid instrument should have to look like its acoustical prototype, but there are certain factors that should probably remain invariant. It would seem appropriate to identify some of these invariants.

Certain controlling principles need to be remembered:

1. Music is a human activity; the instrument is only an extension of a human performer. Any change in the configuration of the instrument should not sacrifice compatibility with the performer, the composer, or the listener.

2. Since a large repertoire of music and a developed technique already exist, the hybrid instrument should be playable with a minimum of change in the habit patterns which a player has learned in order to perform upon an acoustical instrument.

3. The instrument should be economically competitive with the acoustical instrument. One of the most important reasons for developing a hybrid instrument is the shortage and high price of acoustical instruments; the problem of instrument availability cannot be solved with an instrument which is too expensive for the average income.

4. The instrument needs to be musically competitive, in the sense that it should be able to do most of the things which the acoustical instrument can do, and hopefully, some other things as well.

5. The configuration of the instrument should be pleasing in an aesthetic sense.

In the literature on the cello there does not seem to have been any attempt to identify those features of the instrument which are minimally necessary to the player, probably because there has been no reason to do so. To identify some of these features, it was decided to attempt the construction of a hybrid instrument which retained only those features of the acoustical instrument which are necessary to the string or to the player. After several false starts, the fabrication of this instrument began in August 1975.

The first decision to be made in the construction of this "minimum cello" was the matter of size. It is possible to make a hybrid cello smaller than the standard

size without the sacrifice in tone quality that is involved when an acoustical instrument is reduced in size. Several reasons can be given for retaining the normal size at this point: first, the length of the string determines the size of the intervals on the fingerboard, and a cellist spends years learning what these sizes are in various registers. If the hybrid instrument is to be compared to an acoustical instrument, it is best to use the same player for each, because tone quality may vary more widely between two cellists than between two different instruments. Second, the availability of strings of the proper length and gauge is a decided advantage; third, components such as fingerboards, nuts, and tailpieces of the proper size can be bought from a supply house rather than fabricated by hand to the desired dimensions. There may be some advantage to be gained by reducing the size somewhat, especially for smaller people, but for the purposes of this study it was felt best to retain the dimensions of the full-size acoustical cello.

The next design decision involved the speaker: Should an integral speaker be built into the "minimum cello"? Speaker technology continues to develop. It does not seem possible at this time to predict what course it may take in the next several decades, or what size of enclosure will be needed to produce a given SPL with a certain efficiency 30 years in the future. It seems likely that the larger enclosures will continue to be the most efficient, but a technological breakthrough could occur which would invalidate this statement. It was felt that an attempt to predict the form of an instrument based upon unknown future developments could lead to false conclusions: the purpose here is to identify what is essential, not predict the eventual form of an instrument. Because of this, it was planned to use an external speaker for all tests.

For similar reasons, the instrument was planned in a modular form; all electronic components were designed so that they could be used with other instruments as well as the "minimum cello."

Since no speaker enclosure had to be accommodated, the body of the instrument had no other function than to support the strings. Consequently, the body was reduced to a narrow wooden spine; this was fashioned from a piece of redwood two-by-four lumber. The neck was formed from the end of the spine and a cello fingerboard was glued on the top. The peg box was made from three pieces of one-by-two lumber, and handmade pegs were inserted into this pegbox. The most difficult part of the construction was the fitting of the pegs without the special tools which violin makers use for the job.

Other materials could have served as well as wood. The only reason for wooden construction in this case was that special tools were not available and wooden construction was the simplest way to do the job. Furthermore, a reasonably good appearance could be produced with very little additional labor by staining the wood and rubbing it with boiled linseed oil.

Early attempts to play this skeletal cello established that the instrument had a disconcerting tendency to wobble from side to side. The thumb position was practically unusable. Notes in the sixth and seventh positions were unexpectedly difficult to locate because the cues furnished by the edge of the body were lacking. To help these problems, the upper edge of the soundbox was duplicated in outline form: the left side to serve as a guide, the right side to serve as a rest. It was found that for best comfort and playing position, these edges need to be 10 to 15 cm thick. If they are thinner, the neck of the cello tends to rest upon the player's shoulder, which restricts access to the lower positions (those nearest the pegbox). It was also found useful to build a triangular framework at the bottom to give the knees a better chance to steady the instrument. A tailpin was not used during early playing trials, but was added later; the additional stability furnished by the tailpin was found to be very helpful (as it was, of course, when added to the acoustical cello in the 19th century).

The instrument which resulted from these modifications resembled a crossbow more than it did a cello (see Figure 10). However, it sounded very much like an acoustical instrument, and could be played fairly easily by most cellists who tried to do so. The biggest problems had to do with attitude. One player was uncomfortable with the instrument just because it looked so strange, and most were somewhat disconcerted that the sound came from six to ten feet away rather than nearby. However, all who tried the instrument were able to play in tune and produce a good sound.

As with an acoustical instrument, the adjustments which concern the height of the strings above the fingerboard are critical; if the fingerboard is not smooth and the nut and bridge are the wrong height the instrument is nearly unplayable. The curvature of the bridge needs to approximate that of the fingerboard, with a slight roll upwards on the bass side to raise the lower strings (these need more clearance from the fingerboard so that they do not rattle against it). Good heights for the A, D, G, and C strings were four, five, six, and six millimeters, respectively (measurements were taken at the lower end of the fingerboard, from the fingerboard to the nearest edge of the string). At the nut, the upper strings were set one-half millimeter above the fingerboard, the lower strings one millimeter above the fingerboard. Again,

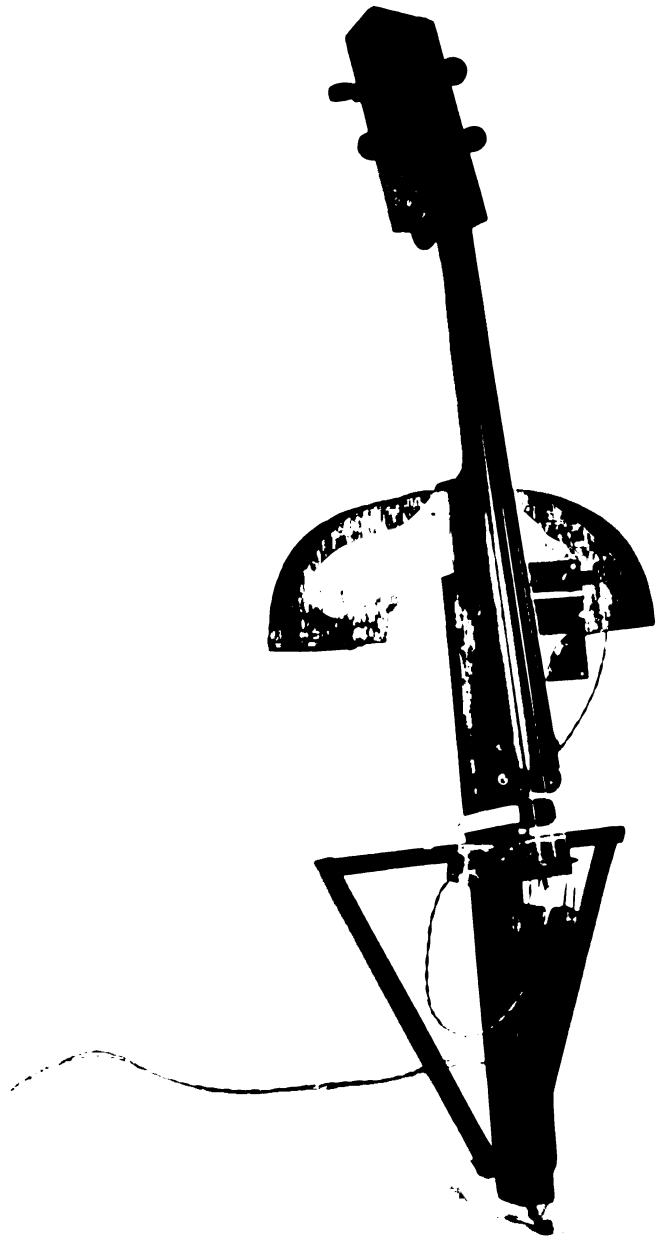

Figure 10.--Hybrid instrument: the minimum cello.

as with an acoustical instrument, if these heights are exceeded by very much, the instrument becomes very difficult to play. If the heights are very much lower than this, the string will buzz against the fingerboard in louder passages.

The pickup system was nearly identical with the one used in the second prototype. However, the magnets were mounted on a steel carrier so that they could be placed in different locations. Experimentation with the magnets produced some interesting effects. As the magnets are moved back and forth near the string, certain overtones seem to cancel. Schelleng mentions in his article on the "Physics of the Bowed String" that the direction of a following bow changes on opposite sides of a bowed string's midpoint; this is caused by the reversal of direction in the shuttling discontinuity which produces the envelope of the string's vibration.[23] There seems to be a similar reversal for each harmonic at its nodal points; this would explain the cancellation effects which can be heard as the magnets are moved back and forth. When the magnet is located at such a node opposite voltages seem to be induced on either side of the node which tends to suppress the harmonic associated with that nodal point. This produced an interesting bell-like timbre

[23]John C. Schelleng, "The Physics of the Bowed String," Scientific American 230 (No. 1): 89-90.

modulation when the magnets are moved while the instrument is being played. The magnets were tried in several different locations to determine the best place. Mathews' location on the bridge was judged by several different professional string players to sound less satisfactory than a location under the end of the fingerboard. Since the magnets are less of a hindrance to playing at that location, they were located there. The point of best sound seems to be at roughly one-seventh the length of the string. The length of the string between nut and bridge in this instrument was about 68-1/2 cm, so the center of the magnet carrier was mounted about 10 cm from the bridge. With this type of mounting the outer strings tend to produce a higher voltage, because they are located closer to the pole pieces. To balance the middle strings against the outer ones extra magnets were put between two pivoted arms of wood; these are brought nearer to the middle strings to equalize their output with the outer strings. A better solution would be to use four adjustable pole pieces (as the better electric guitars do), but this would have taken some machine shop work. Future instruments will probably use adjustable pole pieces, since they are a proven means of solving the problem of string balance.

Either metal or wound-gut strings can be used for an electronic cello. The only requirement is that there must be a continuous conducting path from one end of the string to the other. Different types of strings produce different types of sound, sometimes in an unpredictable fashion. A Prim D string which sounded excellent on a good acoustic cello had a rough quality on the electronic instrument; a Lycon D string which did not sound good on the acoustic cello turned out to be an excellent choice for the electronic instrument. It would be interesting to do a computer-assisted analysis on these strings to determine the reason for this timbre reversal. The strings which are currently in use on the electronic instrument are Lycon A and D strings and Pirastro Eudoxa G and C strings.

One curious effect was noted: on an acoustical instrument bowed notes are very much louder than plucked notes; on this electronic instrument, the opposite is true. Pizzicato playing is very effective on the minimum cello, for the sustaining power and volume of the plucked notes make many techniques and effects possible that cannot be done well on the acoustical instrument. The tone of the electronic cello when bowed resembles that of the acoustical cello, but is subtly different. It is necessary to trim the filter differently for different speaker systems in order to get the best tone. It should be possible to space and balance the filter in such a way that the tone can be an exact match to a first-rate acoustical cello. Originally, it was hoped to use Beauchamp's TONEAN timbre analysis program to derive the filter characteristic of the acoustical cello which has been used as a comparison instrument. The instrument which was used as a comparison, incidentally, is a Joannes Gagliano made in the year 1800. (See Figure 1; the current market value of this instrument is about $10,000.) When analog-to-digital conversion facilities are completed at the MSU audiology laboratories (in the near future), it is planned to do an analysis of several good acoustical instruments to determine what their characteristics are. Currently, the filter for the electronic cello is summed in groups of six resonances; this gives the effect of an octave-band equalizer. To duplicate the tone of a given cello it may be necessary to sum the filter in groups of two resonators, so that one third octave equalization can be used.

In his description of the electronic violin Mathews mentions the sustaining power of his hybrid instrument. In the hybrid instruments built for this project, the ringing time was only slightly greater than that of the acoustical instrument. This was probably due to the fact that a standard cello bridge was used rather than a very massive bridge, as in Mathews' violin.

An interesting possibility which is currently under study is to use some standard synthesizer modules in conjunction with the signal from the filter or from the string. A voltage-controlled amplifier and filter have been built, and an envelope generator is planned. Another possibility, and an exciting one, is the use of a digital filter. At present this approach is very expensive, but there is good reason to believe that within ten years it may be practical in an economic sense. If the signal from the string is converted by a sampling process to a string of binary numbers, it can be processed by a computer (or computer-like circuitry) in almost any fashion desired. The digital filter can be programed to have any desired characteristic which can be specified; in effect it is a universal filter. It can have a very high signal-to-noise ratio (90 decibels have been attained), and it can be made time-variant. For example, a different digital filter characteristic could be used every tenth of a second. Some recent works by Charles Dodge use digital filtering to make musical sounds "talk"; these illustrate some of the possibilities inherent in the digital filter.[24]

Another interesting possibility is the use of additional strings. Since the body of an electronic cello can be made very narrow, it becomes an easy matter to add

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[24]For example, "In Celebration," "Speech Songs," and "The Story of Our Lives," in the album Synthesized Speech Music put out by Composers Recording, Inc., 170 W. 74th St., New York, N.Y. 10023. The record number is CRI SD 348.

strings; the problem of crowding the bowing arc (and of overloading the instrument) is much less severe. Probably the most useful addition would be an additional bass string; a low F string would give the cello nearly as much low range as the bass viol. Another useful addition would be an E string on the top. Many passages would become much easier with an additional string; for example, the Bach Sixth Suite for cello could be played as it was originally written. If the strings are added in pairs the hum cancellation of the differential connection will be preserved. If they are added singly, much the same effect could be had by running a return line under the fingerboard of exactly the same length as the string.

V

CONCLUSIONS

The purpose of this research has been to determine how close our current technology could come to producing a hybrid cello which is a satisfactory musical instrument. The answer to that question: very close indeed. Not only can a useful musical instrument be built, but there are signs that much improvement can be expected over the next few decades. It seems that it will be possible to graft the technical facility and expressive resources of the violin family onto an instrument which can produce a wide variety of timbres over a large dynamic range. The musical potential is obvious. There seems to be no reason why these instruments could not sound exactly like the acoustical violin family, or like the viols, if such is desired. This means that these hybrid instruments could play (legitimately) a repertoire ranging from Morley and Jenkins to Bartok and Penderecki.

Many problems remain to be solved, and many design decisions must be left undecided at this time, but none of the problems met to this point have been insoluble, and most choices involve choosing the best of several possible alternatives. It must not be imagined that the

violin and cello have become obsolete; they are of a far higher order of sophistication than the electronic instruments at this point. But the hybrid instruments show great potential. The next steps in their development depend upon the continued development of electronic technology, the development of better speakers, and the continued decline in price of digital equipment. Industry underwrites a great deal of research in all three fields (for other purposes, of course) so that improved components for an electronic cello can be expected as a serendipitous side effect.

The hybrid instruments are attractive in an economic sense. The most immediate practical application may be in student instruments. Beginners' plywood cellos are currently selling at retail prices of nearly $400. It should be possible to make a better-sounding hybrid instrument for a little over half that amount. In the higher-priced field, the acoustical instruments are still superior. But the acoustical instruments seem to have reached the peak of their development while the hybrid instruments are only beginning theirs. When it is considered that a fine old Italian cello will typically sell for over $10,000, and a Stradivari cello may be over $50,000, then an instrument which is composed of a set of strings, magnets, amplifiers, analog-to-digital and digital-to-analog converter, a small computer, a programmable digital filter, a fine amplifier, and a high quality speaker system begins to look more reasonable.

It seems clear that the hybrid bowed-string instruments have a promising future. Continuing research is planned so that the physical correlates of what is perceived as a good cello sound can be identified. Fine instruments differ, so it seems likely that a number of good combinations may be discovered. Only the delay in delivery and installation of good audio analog-to-digital conversion (at the MSU audiology lab) has delayed this research. It should be possible eventually to design and build an instrument for a desired tone quality, or for several changeable tone colors.

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Much interesting material can also be found in the publications of the "Catgut Acoustical Society." This informal group of scientists, instrument makers, and musicians was inspired by the work of the late Frederic Saunders of Harvard.